Amendments to the Claims

1. (Currently Amended) A method to design a feedback controller for extracting acoustic energy and structural energy in an acoustic enclosure comprising the steps of:

obtaining a continuous-time multi-input multi-output state-space mathematical model of the acoustic enclosure;

designing compensation to render the mathematical model passive in accordance with mathematical system theory if the mathematical model is not passive, thereby forming a compensated system that is passive;

checking passivity of the compensated system; and

designing a passivity-based controller that extracts at least one of acoustic energy or structural energy such that a resulting closed-loop response provides a desired noise reduction.

2. (Canceled).

3. (Currently Amended) The method of claim 1 wherein the step of obtaining a continuous-time multi-input multi-output state-space mathematical model of the acoustic enclosure comprises the step of obtaining a mathematical model having the form according to the equation

$$E\dot{x}(t) = Ax(t) + Bu(t) + Df(t)$$

where A, B, D, and E are matrices given by

$$E = \begin{bmatrix} E_{11} & 0 \\ E_{21} & E_{22} \end{bmatrix} \qquad A = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$$

$$B = \frac{1}{h\rho_0 S_1}\begin{bmatrix} B_{11} \\ 0 \end{bmatrix} \qquad D = \frac{1}{h\rho_0}\begin{bmatrix} D_{11} \\ 0 \end{bmatrix}$$

where E_{11} = I and A_{11} = diag(A_{11}^{nm}) are square matrices of order p_1p_2, E_{22} = I and A_{22} =diag($A_{22}^{k_1k_2k_3}$) are square matrices of order $(l_1 + 1)(l_2 + 1)(l_3 + 1)$, B_{11} is a p_1p_2 x

r matrix, D_{11} is a p_1p_2 x 1 matrix where matrices E_{21}, A_{11}, A_{22}, B_{11}, and D_{11} are given by

$$E_{21} = -\frac{c_0^2 \rho_0}{V} \begin{bmatrix} 0 & 0 & \cdots 0 & 0 \\ 0 & \alpha_{00111} & \cdots 0 & \alpha_{001p_1p_2} \\ & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots 0 & 0 \\ 0 & \alpha_{l_1l_2l_311} & \cdots 0 & \alpha_{l_1l_2l_3p_1p_2} \end{bmatrix}$$

$$A_{11}^{nm} = \begin{bmatrix} 0 & 1 \\ -\omega_{nm}^2 & -2\zeta_{nm}\omega_{nm} \end{bmatrix}$$

$$A_{22}^{k_1k_2k_3} = \begin{bmatrix} 0 & 1 \\ -\omega_{k_1k_2k_3}^2 & -2\zeta_{k_1k_2k_3}\omega_{k_1k_2k_3} \end{bmatrix}$$

$$B_{11} = \begin{bmatrix} 0 & \cdots & 0 \\ \phi_{11}(x_{11}, y_{11}) & \cdots & \phi_{11}(x_{1r}, y_{1r}) \\ \cdots & \cdots & \cdots \\ 0 & \cdots & 0 \\ \phi_{p_1p_2}(x_{11}, y_{11}) & \cdots & \phi_{p_1p_2}(x_{1r}, y_{1r}) \end{bmatrix}$$

$$D_{11} = \begin{bmatrix} 0 \\ \gamma_{11} \\ \cdots \\ 0 \\ \gamma_{p_1p_2} \end{bmatrix}$$

where h is a thickness of the enclosure, ρ_0 is fluid density at equilibrium, S_1 is a boundary surface of the structure, c_0 is the sound speed, V is the volume of the enclosure, α's are coupling coefficients describing the modal interaction between structural and acoustic modes, ω_{ij} denotes natural frequency related to ij-th mode for the structure, ω_{ijk} denotes the acoustical modal frequency for the ijk-th acoustic mode of the enclosure, ζ_{ij} is the damping of the ij-th structural mode shape, ζ_{ijk} is the damping of the ijk-th acoustical mode shape, ϕ_{ij} is the ij-th mode shape of the enclosure structure, and γ_{ij} in matrix D_{11} indicate non-zero coefficients for the direct transmission terms which are functions of modal parameters.

4. (Currently Amended) The method of claim 1 wherein the step of designing a passivity-based controller includes designing a controller having a transfer function G(s) wherein

$$G(s) = Js^2 \sum_{k_1=0}^{l_1} \sum_{k_2=0}^{l_2} \sum_{k_3=0}^{l_3} \frac{\psi_{k_1k_2k_3}(x,y,z)}{s^2 + 2\zeta_{k_1k_2k_3}\omega_{k_1k_2k_3}s + \omega_{k_1k_2k_3}^2} [\sum_{n=1}^{p_1}\sum_{m=1}^{p_2} \frac{\alpha_{k_1k_2k_3nm}\phi_{nm}(x_{11},y_{11})}{s^2 + 2\zeta_{nm}\omega_{nm}s + \omega_{nm}^2}]$$

where $J = \frac{c_0^2\rho_0}{Vh\rho_p S_1}$, h is a thickness of the enclosure, ρ_0 is fluid density at equilibrium, S_1 is a boundary surface of the structure, c_0 is the sound speed, ρ_p is the density of the plate, $\psi_{k_1k_2k_3}(x,y,z)$ are normal modes of a non-homogeneous wave equation, $\omega_{k_1k_2k_3} = c_0\sqrt{\xi_{k_1}^2 + \xi_{k_2}^2 + \xi_{k_3}^2}$ with ξ_{k_1}, ξ_{k2}, and ξ_{k3} being modal coordinates, ζ_{ijk} is the damping of the ijk-th acoustical mode shape, α's are coupling coefficients describing the modal interaction between structural and acoustic modes, and ζ_{ij} is the damping of the ij-th structural mode shape.

5. (Currently Amended) The method of claim 1 wherein the acoustic enclosure has a soft boundary and the step of designing a passivity-based controller includes designing a controller having a transfer function $G_{sb}(s)$ wherein

$$G_{sb}(s) = \sum_{i=1}^{l} \frac{\rho_0 s^2 c_0^2}{h\rho_p S_1} \cdot \frac{\Psi_i(r_0)}{s^2 + \rho_0 c_0^2 s D_{ii}(s) + c_0^2\beta_{ii}} \cdot [\sum_{n=1}^{p_1}\sum_{m=1}^{p_2} \frac{\eta_{inm}\phi_{nm}(x_{11},y_{11})}{s^2 + 2\zeta_{nm}\omega_{nm}s + \omega_{nm}^2}]$$

where Ψ_i denotes the eigenmode function for the acoustic pressure expression obtained using the assumed modes method, η_{inm} is the volume integral term consisting of integrand which is product of structural-acoustic eigenfunctions, ζ_{ij} is the damping of the ij-th structural mode shape, ρ_0 is fluid density at equilibrium, c_0 is the sound speed, S_1 is a boundary surface of the structure, h is a thickness of the enclosure, ρ_p is the density of the plate, ϕ_{ij} is the ij-th mode shape of the enclosure structure, and

$D_{ij}(s) = \int_S \frac{\Psi_j(s)\Psi_i(s)}{Z(r,s)} dS$, $\beta_{ij}(s) = \int_V \nabla\Psi_j(r)\nabla\Psi_i(r) dV$ where Z is the impedance.

6. (Currently Amended) The method of claim 1 wherein the step of designing compensation includes the step of designing a series passifier $C_s(s)$ according to $C_s(s) \approx \begin{cases} \dot{x}_c = A_c x_c + B_c u \\ u' = C_c x_c + D_c u \end{cases}$ wherein Ac, Bc, Cc, and Dc are determined according to the steps comprising:

solving the equation $\begin{bmatrix} A^{**} & (*) & (*) \\ \hat{A} + A^T & YA + A^T Y & (*) \\ \hat{D}^T B^T - CX - D\hat{C} & \hat{B}^T - C & D^{**} \end{bmatrix} < 0$ to obtain $X, Y, \hat{A}, \hat{B}, \hat{C},$ and $\hat{D}$;

constructing matrices M, N, and P such that

$$P\Pi_1 = \Pi_2 \text{ and } \Pi_1^T \Pi_2 = \begin{bmatrix} X & I \\ I & Y \end{bmatrix} \text{ where } XY + MN^T = I,$$

$\Pi_1 = \begin{bmatrix} X & I \\ M^T & 0 \end{bmatrix}$, $\Pi_2 = \begin{bmatrix} I & Y \\ 0 & N^T \end{bmatrix}$, $P = \begin{bmatrix} Y & N \\ N^T * & \end{bmatrix}$; and

solving the equations $\hat{A} = YAX + YBC_c M^T + NA_c M^T$, $\hat{B} = YBD_c + NB_c$, $\hat{C} = C_c M^T$, and $\hat{D} = D_c$ in reverse order to obtain Ac, Bc, Cc, and Dc.

7. (Currently Amended) The method of claim 1 wherein the step of designing compensation comprises the step of designing a feedforward compensator

$C_{ff}(s)$ according to $C_{ff}(s) \approx \begin{cases} \dot{x}_c = A_c x_c + B_c u \\ y_2 = C_c x_c + D_c u \end{cases}$ wherein *Ac*, *Bc*, *Cc*, and *Dc* are determined according to the steps comprising:

solving the equation $\begin{bmatrix} AX + XA^T & (*) & (*) \\ \hat{A} + A^T & YA + A^T Y & (*) \\ B^T - CX - \hat{C} & B^T Y + \hat{B}^T - C & D^\perp \end{bmatrix} < 0$ where $D^\perp = -(D + D^T + \hat{D} + \hat{D}^T)$ to obtain $X, Y, \hat{A}, \hat{B}, \hat{C}$, and $\hat{D}$;

constructing matrices *M*, *N*, and *P* such that

$P\Pi_1 = \Pi_2$ and $\Pi_2^T \widetilde{A} \Pi_1 = \begin{bmatrix} AX & A \\ YAX + NA_c M^T & YA \end{bmatrix}$ where $XY + MN^T = I$,

$\Pi_1 = \begin{bmatrix} X & I \\ M^T & 0 \end{bmatrix}$, $\Pi_2 = \begin{bmatrix} I & Y \\ 0 & N^T \end{bmatrix}$, $P = \begin{bmatrix} Y & N \\ N^T & * \end{bmatrix}$; and

solving the equations $\hat{A} = YAX + NA_c M^T$, $\hat{B} = NB_c$, $\hat{C} = C_c M^T$, and $\hat{D} = D_c$ in reverse order to obtain *Ac*, *Bc, Cc*, and *Dc*.

8. (Original) The method of claim 1 wherein the step of designing compensation comprises the step of performing sensor blending if there are redundant sensors.

9. (Original) The method of claim 1 wherein the step of designing compensation comprises the step of performing control allocation if there are redundant actuators.

10. (Original) The method of claim 1 wherein the step of designing compensation to render the mathematical model passive comprises the steps of:

determining if a feedforward compensation will passify the system;

if a feedforward compensation will not passify the system:

designing a constant gain feedforward compensation to render the compensated system minimum-phase; and

rendering the compensated system positive-real by at least one of series compensation, sensor-blending and control allocation.

11. (Original) The method of claim 10 wherein the step of designing a passivity-based controller comprises the step of designing one of a dissipative linear-quadratic-Gaussian (LQG) type positive-real controller and a dissipative constant gain positive-real controller.

12. (Original) The method of claim 10 wherein the step of rendering the compensated system positive-real by at least one of series compensation, sensor-blending and control allocation comprises the step of rendering the compensated system positive-real by at least one of series compensation, feedback compensation, hybrid compensation, and sensor-blending and control allocation.

13. (Currently Amended) The method of claim 1 further comprising the step of redesigning the compensation if the passivity is not preserved~~ if mathematical model parameters are perturbed from nominal values~~.

14.(Currently Amended) The method of claim 1 further comprising the step of performing numerical simulations of the controller in the presence of a simulated broadband disturbance input~~ to determine if the closed-loop response is satisfactory~~.

15. (Original) The method of claim 14 further comprising the step of redesigning the controller if the closed-loop response is not satisfactory.

16. (Original) The method of claim 1 wherein the step of designing compensation comprises the steps of:

designing a constant gain feedforward compensation to render the compensated system minimum-phase; and

rendering the compensated system positive-real by one of sensor-blending and control allocation.